Frequency Probe Measurements in Processing Plasmas

D.R. Boris, S.G. Walton, M. Baraket, E.H. Lock, and R.F. Fernsler,
Plasma Physics Division, U.S. Naval Research Laboratory, Washington, DC

ABSTRACT

Plasma density measurements are an essential tool in understanding and controlling processing plasmas across a wide range of applications. Charge collection probes (Langmuir probes) are of limited utility in depositing plasmas, or in processes that require the use of reactive gases, as these environments result in unreliable data acquisition. Plasma frequency probes are an attractive alternative to Langmuir probes in such applications since they do not suffer performance degradation in these environments. Frequency probes have demonstrated the ability to measure plasma density over a range of 10^8 to 10^{12} cm^{-3} and, it is possible to extract the plasma potential and electron temperature. Previous work has focused on plasma frequency probe measurements in plasmas that are uniform over the dimensions of the vacuum vessel. This paper focuses on the unique challenge of making plasma density measurements in electron beam generated plasmas which are highly non-uniform with strong plasma density gradients remote from surfaces. Frequency probe measurements have been compared to Langmuir probe measurements for a variety of experimental conditions in an electron beam generated plasma processing system.

INTRODUCTION

Frequency Probes

The Naval Research Laboratory is developing plasma frequency probes for use as a diagnostic in electron beam generated plasma processing systems. Plasma frequency probes operate on the principles of antenna impedance in a plasma, an area that incorporates an extensive body of research going to back to the early 1960s [1-8]. The use of frequency probe measurements for space physics research has been a fairly active field for some time [9-11], but there are other applications as well. Plasma frequency probes are of interest for any application where electron density measurements are desired but difficult, or impossible to get using Langmuir probes; ion thrusters [12], reactive processing plasmas [13], and depositing plasmas are examples of environments where Langmuir probe measurements can be difficult.

Electron Beam Generated Plasma Processing System

This work focuses specifically on developing frequency probe diagnostics for use in the electron beam generated plasma processing systems which are used in a number of plasma based materials modification applications at NRL including etching [16] nitriding [17], thin film deposition, and polymer surface activation [19]. Electron-beam-produced plasmas differ from conventional plasma processing sources because ionization and excitation processes in the plasma are driven by a high energy electron beam instead of low energy discharge electrons. Electron beam generated plasmas have been shown to offer high densities (10^{10} to 10^{11} cm^{-3}), low electron temperature (< 1 eV) [14, 15, 20], low incident ion energies [21], and unique species densities. In addition, these plasmas represent a localized, scalable plasma source that is decoupled from the vacuum chamber geometry. The system specific to this paper utilizes a steady state hollow cathode plasma electron source to produce an electron beam which is confined to a thin, large area, sheet with an axial magnetic field. This geometry produces a high-density plasma over the volume of the beam [14, 15], with decaying plasma density outside the beam volume.

Previous experimental work investigating the behavior of frequency probes focused on plasmas that were largely uniform over the dimensions of the vacuum vessel. Understanding the behavior of frequency probes in non-uniform plasmas presents an interesting challenge. For the electron beam plasma geometry described above the plasma is highly localized to a region remote from the vacuum vessel walls; this work focuses on exploring how the unique geometry of the electron beam plasma system affects the behavior of plasma frequency probes.

EXPERIMENTAL SETUP

Processing Chamber and Electron Beam Source

The electron beam plasma processing chamber consists of a large, rectangular, stainless steel, vacuum vessel (width – 120 cm, height – 55 cm, and length - 120 cm). Along the length of the chamber are magnetic field coils that produce a uniform axial magnetic field within the confines of the vacuum chamber. Within the vacuum vessel are the plasma processing components; the electron beam source, provided by Sigma Technologies Int'l Inc., a movable processing stage, a termination anode for the electron beam, and Langmuir probe and plasma frequency probe diagnostics. A diagram of the electron beam plasma chamber is shown in Figure 1.

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The electron source is capable of providing a sheet of high energy electrons with energies as large as 5 keV. When a negative high voltage is applied to the linear cathode a high density, DC glow discharge plasma is formed within the source. The electrons emitted from the cathode (via ion impact) are accelerated across the high voltage cathode sheath, producing the high energy beam. The magnetic field confines the beam electrons to a sheet geometry creating a similarly shaped plasma. For the results reported here the cathode voltage was -2 kV.

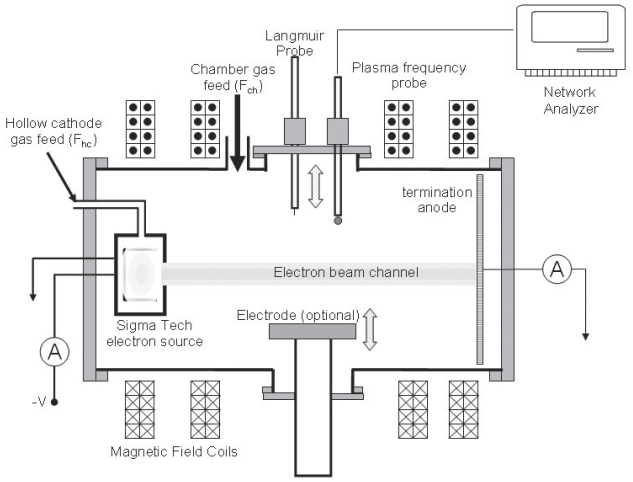

Figure 1: Diagram of the electron beam plasma processing chamber showing plasma diagnostic configuration.

This setup allows for the production of high density, low temperature plasma over the beam volume; outside the beam the density decays while the temperature remains nearly constant. Figure 2 shows electron density and electron temperature profiles for Ar and an Ar/N_2 mixture under typical operating conditions, measured using a Langmuir probe.

Plasma Diagnostic Setup

The plasma frequency probe used for these experiments consists of a small stainless steel sphere of radius 1.5 mm attached to end of a piece of rigid coaxial cable. The probe is then connected to an HP 8753D Network Analyzer through 50 Ω, RG 303 coaxial cable. When connected to the network analyzer the complex reflection coefficient, Γ, is measured and the impedance of the system calculated according to:

$$Z = Z_0 \frac{1+\Gamma}{1-\Gamma} \qquad (1)$$

where Z_0 is the analyzer internal impedance of 50 Ω. This measurement technique relies on the user's ability to properly calibrate the probe to eliminate stray capacitances and inductances. This is done by building a matched 50 Ω load, an electrical short, and open termination which are calibrated

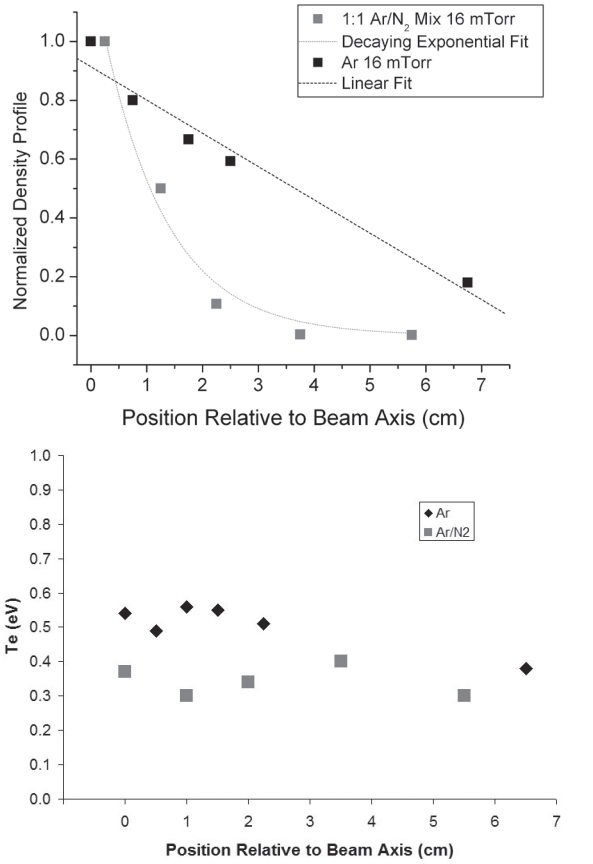

Figure 2: (a) plasma density profile in Ar and a 1/1 Ar/N_2 mixture (absolute peak densities were $1.5x10^{11}$ cm^{-3} for Ar and $2.8x10^{10}$ cm^{-3} for Ar/N_2) (b) electron temperature profile for Ar and a 1/1 Ar/N_2 mixture. Chamber pressure was 16 mTorr in both cases.

to provide Γ values of 0, –1, and 1, respectively. This allows stray capacitance from the cabling and other components to be eliminated. References 10 and 11 explain this procedure in detail. Once this calibration is completed, the network analyzer can properly measure and interpret the plasma impedance characteristics obtained with the plasma frequency probe.

Measurements by the plasma frequency probe are benchmarked by a cylindrical Langmuir probe. The Langmuir probe consists of a thin loop of wire 3 mm in length with a collection area of $1.5x10^{-2}$ cm^2. The diagnostic and data acquisition routines follow those previously discussed (Lock et al., Plasma Sources) [22]. This provides a local plasma measurement against which to compare the frequency probe. This is invaluable since it is unclear over what volume the plasma frequency probe samples. Both the Langmuir probe and plasma frequency probe are mounted on the top of the electron beam plasma chamber with linear motion feedthroughs that allow ≈20 cm of motion through the vacuum vessel, perpendicular to the beam axis.

RESULTS

A frequency probe provides unambiguous measurement of the plasma frequency due to two unique plasma impedance features which are unique to the plasma frequency. The network analyzer measures a maximum in the real component of the plasma impedance at the plasma frequency while at the same time measuring a zero-crossing in the imaginary impedance. Typical measurements are shown in Figure 3.

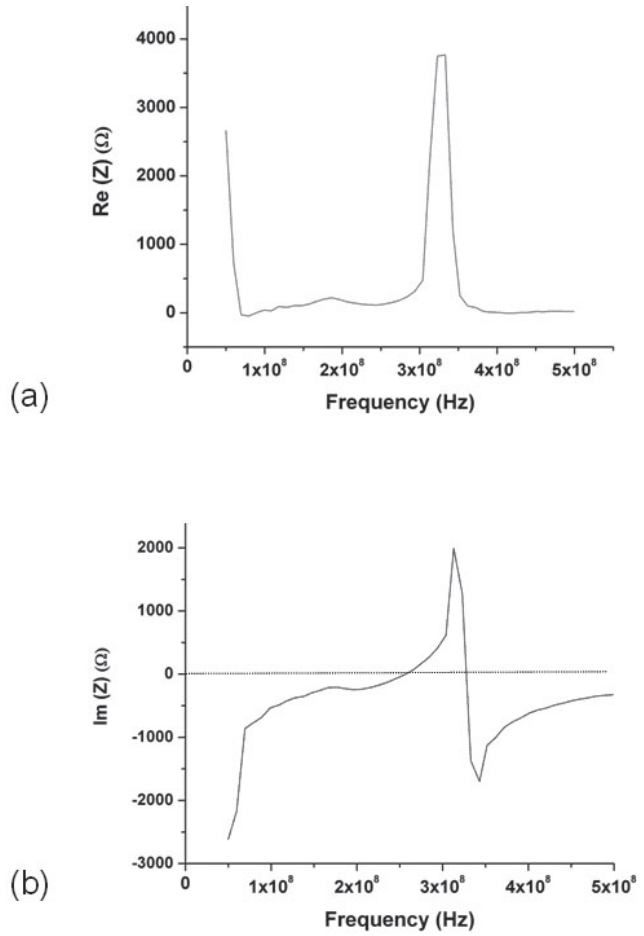

Figure 3: (a) Real part of the plasma impedance showing maximum at f_{pe}. (b) Imaginary part of the plasma impedance showing zero crossing at f_{pe}. No axial magnetic field present.

The measurements in Figure 3 were taken in an, un-magnetized, electron beam generated plasma where the beam is allowed to spread to fill the chamber. This creates a relatively uniform, but diffuse plasma throughout the vacuum vessel. Under these conditions the Langmuir probe and frequency probe recorded the same plasma density to within ±30%. Alternatively, when an axial magnetic field is introduced two complications arise: (1) the impedance resonance moves from the plasma frequency to the upper hybrid frequency (due to the influence of the magnetic field on electron motion), and (2) the beam generated plasma becomes highly non-uniform with significant density gradients on the size scale comparable to the probe dimensions [23]. In this case the magnetic field must be well characterized and uniform in order to calculate the plasma density from the resonant frequency using

$$\omega_{pe} \rightarrow \omega_{uh} = \sqrt{\left(\omega_{pe}^2 + \omega_{ce}^2\right)} \tag{2a}$$

$$n_e = \frac{m_e \varepsilon_0}{e^2}\left(\omega_{uh}^2 - \omega_{ce}^2\right) \tag{2b}$$

where ω_{uh} is the upper hybrid frequency and ω_{ce} is the electron cyclotron frequency. The magnetic field profile in the chamber has been well characterized using magnetic field probes, so this added parameter should not interfere with calculating the plasma density. The more pertinent question regards the effect that the strong density gradients imposed by the magnetically confined electron beam have on frequency probe resonance measurements.

Using the above correction for the cyclotron frequency, density profiles of the electron beam generated plasma, as well as parametric studies of fill gas pressure, and electron beam energy, were obtained using the plasma frequency probe. The results are shown below in Figures 4 and 5 and are benchmarked against a Langmuir probe taking traces at essentially the same location within the plasma sheet. In the beam energy scan it should be noted that increasing cathode voltage caused a corresponding linear increase in the cathode current accounting for the increase in plasma density.

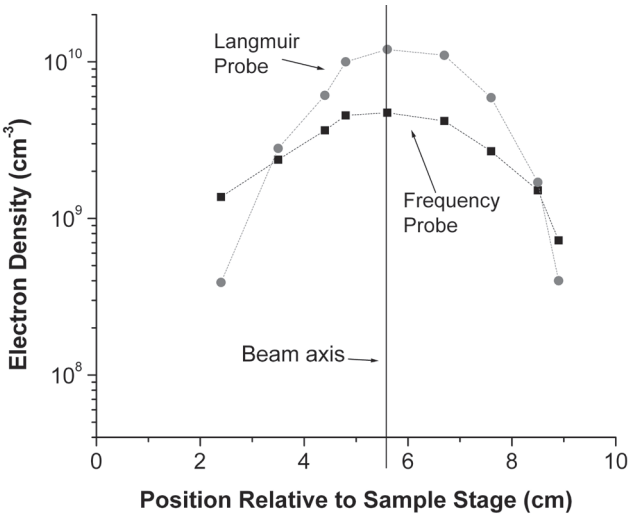

Figure 4: Plasma density profile measured by a Langmuir probe and plasma frequency probe. The chamber pressure was 16 mTorr and the axial magnetic field was 150 Gauss.

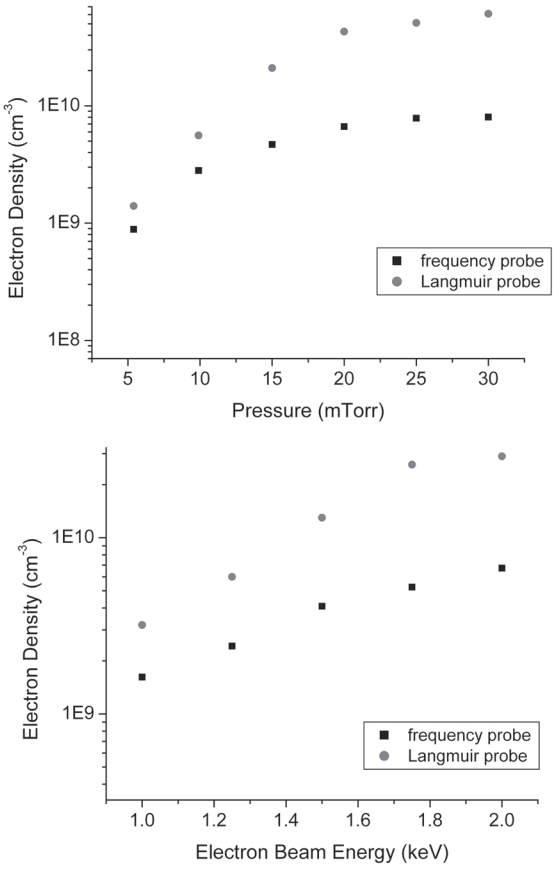

Figure 5: (a) Pressure scan in argon with 2 kV beam energy (b) Beam energy (cathode voltage) scan in argon with pressure held at 22 mTorr. Magnetic field was 150G in both cases. Note that beam current increased linearly with increasing cathode voltage. All the measurements were taken on the beam axis where maximum plasma density was measured by the Langmuir probe.

The plasma frequency probe and Langmuir probe both measure density profiles that are peaked near the beam axis (Figure 4). However, the absolute densities measured by the frequency probe are substantially different from the Langmuir probe. It is thought that the non-locality of the frequency probe measurements and the strong plasma gradients are the likely cause of this disagreement. Density gradients such as those shown in Figure 4 significantly affect the resonance behavior of the plasma as measured by the frequency probe. The real component of the complex plasma impedance, Re($Z(\omega)$), in an un-magnetized plasma, is governed by

$$\mathrm{Re}(Z(\omega)) = \frac{\omega}{4\varepsilon_0 r_{rf}^2}\left(\frac{1}{\left(d\omega_{pe}^2/dr\right)}\right)_{\omega=\omega_{pe}} \qquad (3)$$

A more in-depth discussion of the derivation of this expression can be found in Ref. 10. The term r_{rf} refers to the radial location with respect to the probe center at which the plasma frequency resonance occurs for a given ω. The amplitude and frequency of the resonance in Re($Z(\omega)$) are governed by the gradient of the plasma density (the term $d\omega_{pe}^2/dr$), as well as by the radius, r_{rf}, at which the resonance occurs. Thus, in order for a strong resonance to be measured at the bulk plasma frequency, the density surrounding the probe must asymptote to the bulk plasma density, and remain at the bulk plasma density over the effective sampling volume of the plasma frequency probe. This effective sampling volume is governed by the $(4\varepsilon_0 r_{rf}^2)^{-1}$ scaling in Equation 3. The interpretation of this expression is further complicated by the fact that the electrostatic waves generated by the probe propagate in a spherically symmetric manner whereas the electron beam generated plasma appears as a slab geometry to the probe. Thus, r_{rf} will vary in θ as well as r in this geometry. Indeed, for a given frequency there are multiple values of r_{rf} where a resonance occurs. Thus, resonant frequencies in e-beam plasmas occur over a broad volume and at multiple frequencies which need not be explicitly correlated with the maximum plasma density in the system. This suggests an explanation as to why the Langmuir probe and the plasma frequency probe exhibit the same trends as plasma parameters are varied but do not agree on an absolute scale. We are presently researching techniques to correct for these plasma non-uniformity effects.

CONCLUSIONS

This work has shown that the interpretation of plasma frequency probe data is quite complex in plasmas with strong density gradients. The data, in conjunction with previous analytical and experimental work done on collisionless energy absorption, indicates that the frequency probe samples the plasma over an effective volume within the plasma. We are currently researching a more robust understanding of the manner in which the plasma frequency probe samples a non-uniform plasma in a magnetic field in the hopes that an analytic expression for highly non-uniform magnetized plasmas will provide a correction to the acquired data.

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